

THE EFFECTS OF REINFORCEMENT FREQUENCY AND RESPONSE REQUIREMENTS ON THE MAINTENANCE OF BEHAVIOR

DAVID P. RIDER AND BRIAN J. D'ANGELO

LOUISIANA STATE UNIVERSITY MEDICAL CENTER AND
UNIVERSITY OF MONTANA

Six rats responded under fixed-interval and tandem fixed-interval fixed-ratio schedules of food reinforcement. Basic fixed-interval schedules alternated over experimental conditions with tandem fixed-interval fixed-ratio schedules with the same fixed-interval value. Fixed-interval length was varied within subjects over pairs of experimental conditions; the ratio requirement of the tandem schedules was varied across subjects. For both subjects with a ratio requirement of 10, overall response rates and running response rates typically were higher under the tandem schedules than under the corresponding basic fixed-interval schedules. For all subjects with ratio requirements of 30 or 60, overall response rates and running response rates were higher under the tandem schedules than under the corresponding basic fixed-interval schedules only with relatively short fixed intervals. At longer fixed intervals, higher overall response rates and running rates were maintained by the basic fixed-interval schedules than by the tandem schedules. These findings support Zeiler and Buchman's (1979) reinforcement-theory account of response strength as an increasing monotonic function of both the response requirement and reinforcement frequency. Small response requirements added in tandem to fixed-interval schedules have little effect on reinforcement frequency and so their net effect is to enhance responding. Larger response requirements reduce reinforcement frequency more substantially; therefore their net effect depends on the length of the fixed interval, which limits overall reinforcement frequency. At the longest fixed intervals studied in the present experiment, reinforcement frequency under the tandem schedules was sufficiently low that responding weakened or ceased altogether.

Key words: output, tandem fixed-interval fixed-ratio schedules, fixed-interval schedules, reinforcement frequency, response requirements, reinforcement theory, lever press, rats

Reinforcement schedules specify the relationship between operant behavior and a reinforcing stimulus. Schedules differ in the extent to which they limit reinforcement frequency and constrain response output (i.e., the number of responses that can occur between successive reinforcer deliveries). At one end of a continuum, response requirements of ratio schedules impose maximal constraint on output by setting both upper and lower limits on the number of responses that can occur per reinforcer. Reinforcement frequency is not limited by ratio schedules but depends strictly on the rate at which responses occur. Near the opposite end of the continuum, interval schedules impose minimal constraint on output by setting only a lower limit (i.e., one) on the number of responses that can occur per rein-

forcer. Reinforcement frequency is limited by the length of the interval, but the number of responses per reinforcer depends on the rate at which responses occur.

Ratio schedules typically maintain higher response rates than do interval schedules over a limited range of schedule parameters (e.g., Catania, Matthews, Silverman, & Yohalem, 1977; Ferster & Skinner, 1957; Killeen, 1969; Kintsch, 1965; Matthews, Shimoff, Catania, & Sagvolden, 1977; Rider, 1977, 1980, 1982; Shimoff, Matthews, & Catania, 1986; Williams, 1968; Zuriff, 1970). The tendency for ratio schedules to generate higher response rates than interval schedules do has been attributed to subjects' tendencies toward maximizing reinforcement frequency and minimizing response cost (e.g., Baum, 1981). However, interval schedules can maintain many more responses per reinforcer, on the average, than ratio schedules can (Ferster & Skinner, 1957, pp. 399-407, 518-520; Zeiler, 1977, 1979). Further, the addition of multiple-response requirements to interval schedules often reduces response rate below that maintained by the interval schedule alone (e.g., Herrnstein & Morse, 1958; Zeiler & Buchman, 1979). Because reinforcement frequency decreases with

This research was conducted at the University of Montana. We are grateful to Carl D. Cheney, Lewis S. Seiden, and Michael D. Zeiler for equipment used to conduct this research. We thank Nora N. Kametani for help in the laboratory and Rick, Ted, Ozzy, Pete, Elvis C., and Bon for assistance in the collection of data. Reprints can be obtained from David P. Rider, Louisiana State University Medical Center, School of Allied Health Professions, Human Development Center, 1100 Florida Avenue, New Orleans, Louisiana 70119.

such reductions in response rate, these findings do not support accounts of behavior that are based on principles of maximization of reinforcement frequency.

Zeiler and Buchman (1979) added fixed-ratio (FR) requirements to basic fixed-interval (FI) schedules and compared pigeons' responding under FI with that under tandem FI FR and conjunctive FI FR schedules. The tandem schedules provided reinforcers upon completion of the FI and FR requirements in succession; the conjunctive schedules provided reinforcers upon completion of both FI and FR requirements, regardless of the order of completion. Under each scheduling arrangement, small FR requirements enhanced response rate but larger FR requirements reduced response rate relative to that maintained by the FI schedule alone. Similar findings were obtained with other measures of response strength, including the running rate (the rate of responding from the first to the final response within interreinforcement intervals), number of responses within the FI period of tandem or conjunctive FI FR, and response rate within the FR period of tandem or conjunctive FI FR. Thus, for a variety of measures of responding under both tandem and conjunctive FI FR schedules, response output was a bitonic function of the response requirement.

Zeiler and Buchman (1979) proposed an explanation for this bitonic output function that is based on the joint operation of two variables. According to their account, response strength is an increasing monotonic function of both the response requirement and the frequency of reinforcement. Responding is enhanced by increasing response requirements but is diminished by the accompanying reductions in reinforcement frequency. Small FR requirements added to a basic FI schedule affect reinforcement frequency minimally and so the net effect is enhanced responding. Relatively large added FR requirements result in considerable decrements in reinforcement frequency; therefore, the net effect is reduced responding.

Zeiler and Buchman (1979) concluded that the effects of added response requirements to basic FI schedules are independent of the length of the FI. They manipulated FI length between subjects, with 1 pigeon per FI value. No systematic differences in the effects of added response requirements were seen across FI val-

ues ranging from 3 to 30 min. This is surprising in light of the fundamental role reinforcement frequency plays in the maintenance of behavior (e.g., Herrnstein, 1970). Whatever the size of the added response requirement, reinforcement frequency must remain sufficiently high to maintain at least the required number of responses per reinforcer; otherwise, no reinforcers would be obtained and responding would cease. But obtained reinforcement frequency under conjunctive or tandem FI FR schedules depends on both the size of the added response requirement and the length of the FI. Very small added response requirements that have little effect on reinforcement frequency may enhance responding regardless of the length of the basic FI schedule. However, the net effect of larger response requirements that substantially reduce reinforcement frequency may depend on the length of the FI.

Consider the impact of adding an FR 60 requirement in tandem with various FI schedules. An FR 60 requirement in tandem with very short FIs is hardly different from an FR 60 alone; it is equivalent to FR 61, in fact, when the postreinforcement pause approaches or exceeds the FI value. Although reinforcement frequency surely would be reduced by the added FR requirement, it likely would remain high enough to maintain relatively high rates of responding. But with a sufficiently long FI, which limits overall reinforcement frequency directly, the same added FR requirement may further reduce the obtained frequency of reinforcement enough to induce ratio strain (cf. Ferster & Skinner, 1957).

The present study addresses the possibility that FI length mitigates the effects of added FR requirements in tandem with basic FI schedules. Responding under FI schedules was compared with responding under tandem FI FR schedules, with FI length manipulated within subjects and FR size manipulated between subjects.

METHOD

Subjects

Six male albino rats of Sprague-Dawley descent were maintained at 80% of their respective free-feeding weights. All were about 4 months old and experimentally naive at the start of the experiment.

Table 1

Sequence of experimental conditions, in parentheses, and number of sessions each was in effect.

Schedule	Number of sessions (order of presentation)					
	Rat 190	Rat 191	Rat 192	Rat 193	Rat 194	Rat 195
FI 15 s	29 (1)	32 (1)	29 (1)	35 (1)	44 (1)	60 (1)
Tandem FI FR	23 (2)	13 (2)	27 (2)	19 (2)	75 (2)	26 (2)
FI 30 s	—	—	—	—	31 (9)	—
Tandem FI FR	—	—	—	—	27 (10)	—
FI 1 min	84 (3)	20 (3)	49 (3)	34 (3)	50 (3)	63 (3)
Tandem FI FR	45 (4)	24 (4)	18 (4)	34 (4)	51 (4)	30 (4)
FI 2 min	—	—	36 (7)	—	25 (7)	—
Tandem FI FR	—	—	115 (8)	—	14 (8)	—
FI 4 min	23 (5)	31 (5)	23 (5)	102 (5)	86 (5)	45 (5)
Tandem FI FR	61 (6)	41 (6)	10 (6)	24 (6)	11 (6)	37 (6)
FI 8 min	38 (7)	61 (7)	43 (9)	97 (7)	—	36 (7)
Tandem FI FR	22 (8)	116 (8)	15 (10)	56 (8)	—	64 (8)
FI 16 min	50 (9)	61 (9)	—	66 (9)	—	47 (9)
Tandem FI FR	61 (10)	46 (10)	—	71 (10)	—	30 (10)
FI 32 min	49 (11)	43 (11)	—	39 (11)	—	—
Tandem FI FR	49 (12)	44 (12)	—	29 (12)	—	—

Apparatus

The experimental chamber was constructed of stainless steel and Plexiglas and measured 30.9 cm long, 24.6 cm wide, and 27.3 cm high. A BRS/LVE lever, 2.9 cm wide and 1.0 cm thick, protruded 3.1 cm from the front wall of the chamber, 4.0 cm from the left side wall and 4.3 cm above the grid floor. A minimum downward force of 0.20 N on the lever was required to close a microswitch and register as a response. A BRS/LVE pellet chute (RPC-001) was centered midway between the side walls of the chamber at the base of the front wall. Noyes 45-mg precision food pellets were dispensed into the pellet chute as reinforcers. Illumination during experimental sessions was provided by three miniature lamps (bulb type 1819) mounted 5.0 cm directly above the lever and a houselight (bulb type 1820) mounted on the front wall, 2.5 cm from the ceiling and midway between the side walls.

The experimental chamber was enclosed in a sound-attenuating cubicle. A fan attached to the cubicle ventilated the experimental space and a speaker inside the cubicle provided white noise. Electromechanical equipment across the room controlled reinforcement contingencies and collected data.

Procedure

Lever pressing was acquired over the course of four 60-min pretraining sessions during

which each lever press was reinforced. In addition, a reinforcer was delivered at 60-s intervals independently of responding during the first two pretraining sessions.

After pretraining, FI and tandem FI FR schedules alternated over experimental conditions so that each pair of conditions consisted of a basic FI followed by tandem FI FR with the same FI value. The FI value was changed after each pair of conditions. For each tandem-schedule condition, the FR value was 10 for Rats 190 and 191, 30 for Rats 192 and 193, and 60 for Rats 194 and 195. No stimulus change in the experimental chamber corresponded with completion of the FI component in the tandem schedules.

Experimental conditions were changed only when responding was considered stable: Overall response rate in each of five consecutive sessions had to be within 15% or five responses per minute of the 5-day mean response rate, whichever was greater. The sequence of experimental conditions and number of sessions each was in effect are presented in Table 1.

Experimental sessions were conducted 7 days per week at about the same time each day. In all conditions in which the FI value was less than 32 min, sessions were terminated with the first reinforcer delivery after 60 min or after 75 min even if a reinforcer had not been delivered. When the FI value was 32 min, sessions lasted until the first reinforcer delivery after 3 hr.

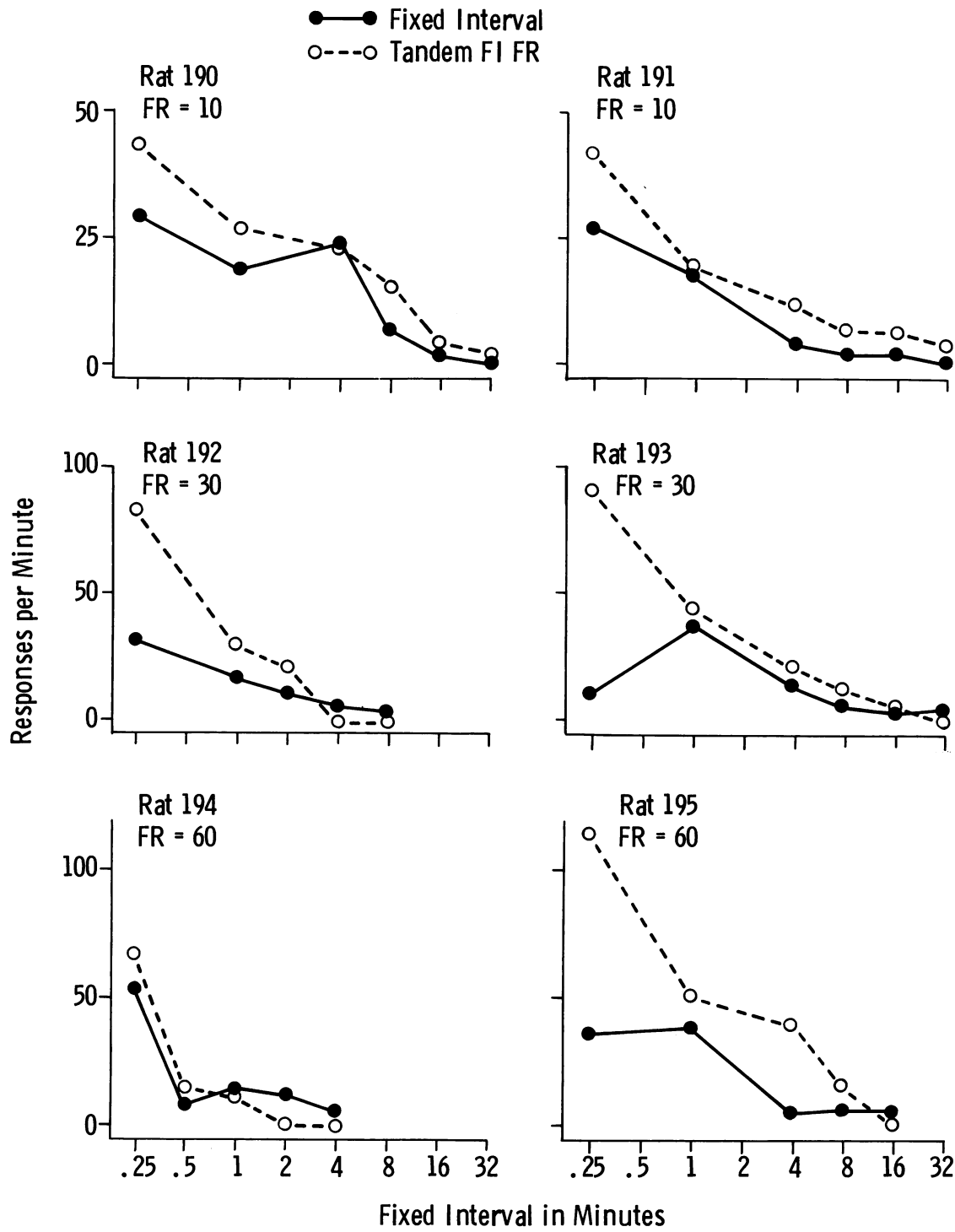


Fig. 1. Mean overall response rates from the last five sessions of each experimental condition.

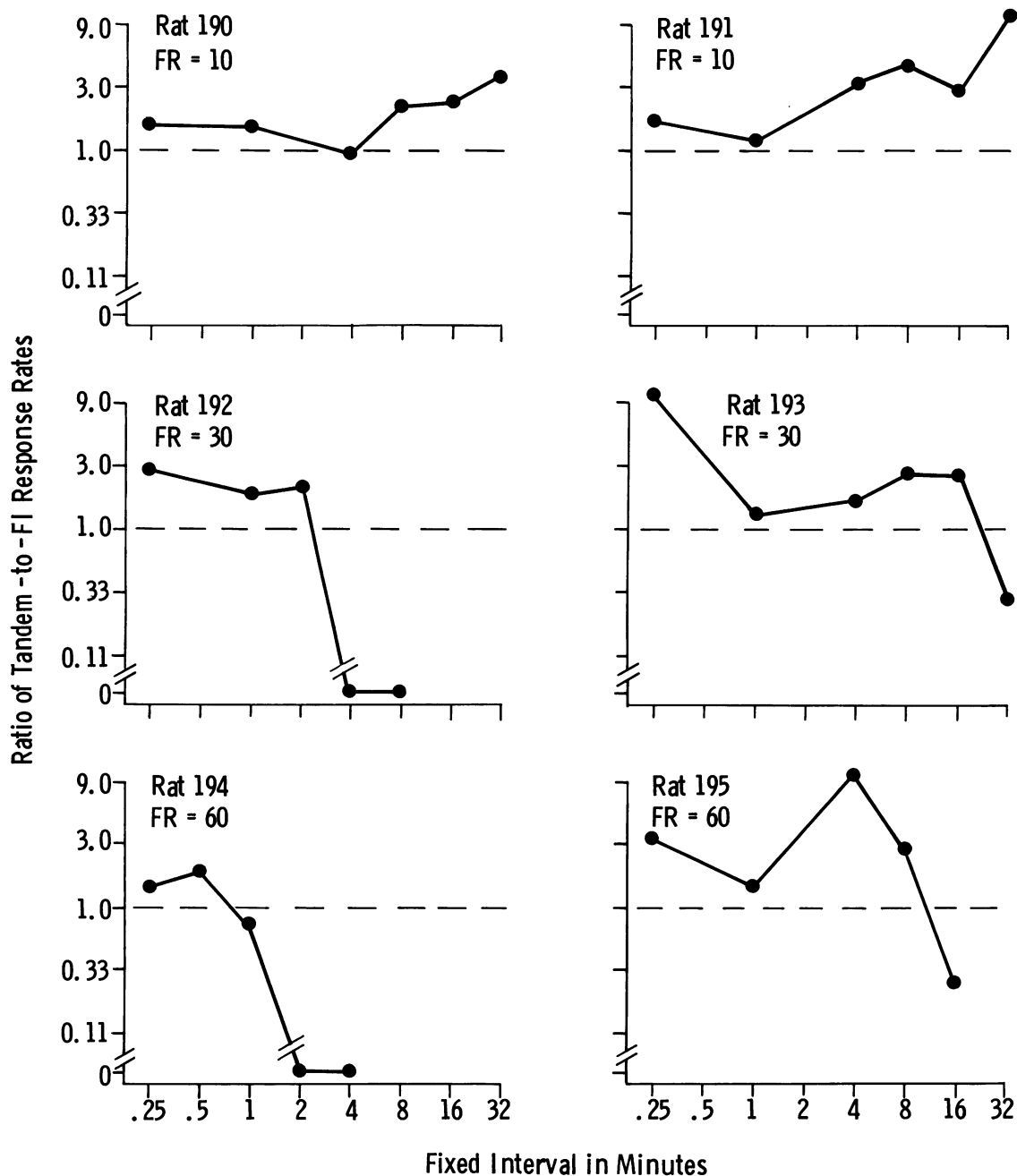


Fig. 2. Ratios of mean overall response rates under tandem FI FR schedules to mean overall response rates under the corresponding basic FI schedules from the last five sessions of each experimental condition.

RESULTS

Figure 1 shows mean overall response rates from the last five sessions of each condition. Response rates typically decreased as the FI value increased, both under basic FI schedules

and under tandem FI FR schedules. At the shortest FI value, a higher rate of responding was maintained by the tandem FI FR schedule than by the FI schedule alone for each rat. For rats with the added FR 10 requirement, tandem FI FR schedules continued to maintain

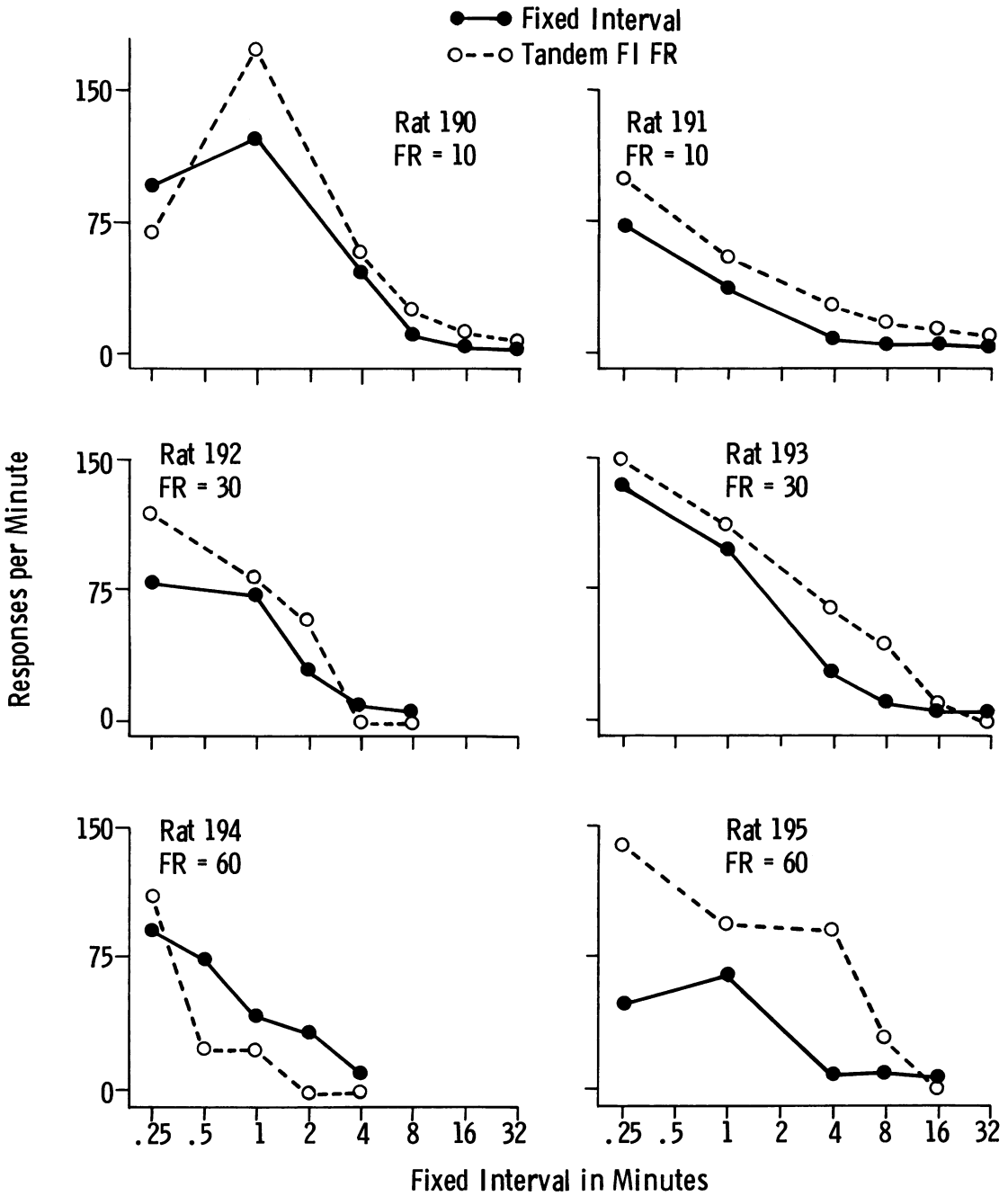


Fig. 3. Mean running response rates from the last five sessions of each experimental condition.

higher response rates than those maintained by the corresponding basic FI schedules, with the exception of tandem FI 4 min FR 10 for Rat 190. For rats with FR 30 or FR 60 response requirements, the effect of the added

FR requirement depended on the length of the basic FI. At relatively short FI values, higher response rates were maintained by the tandem FI FR schedules than by the FI schedules alone. At the longest FI values studied for these

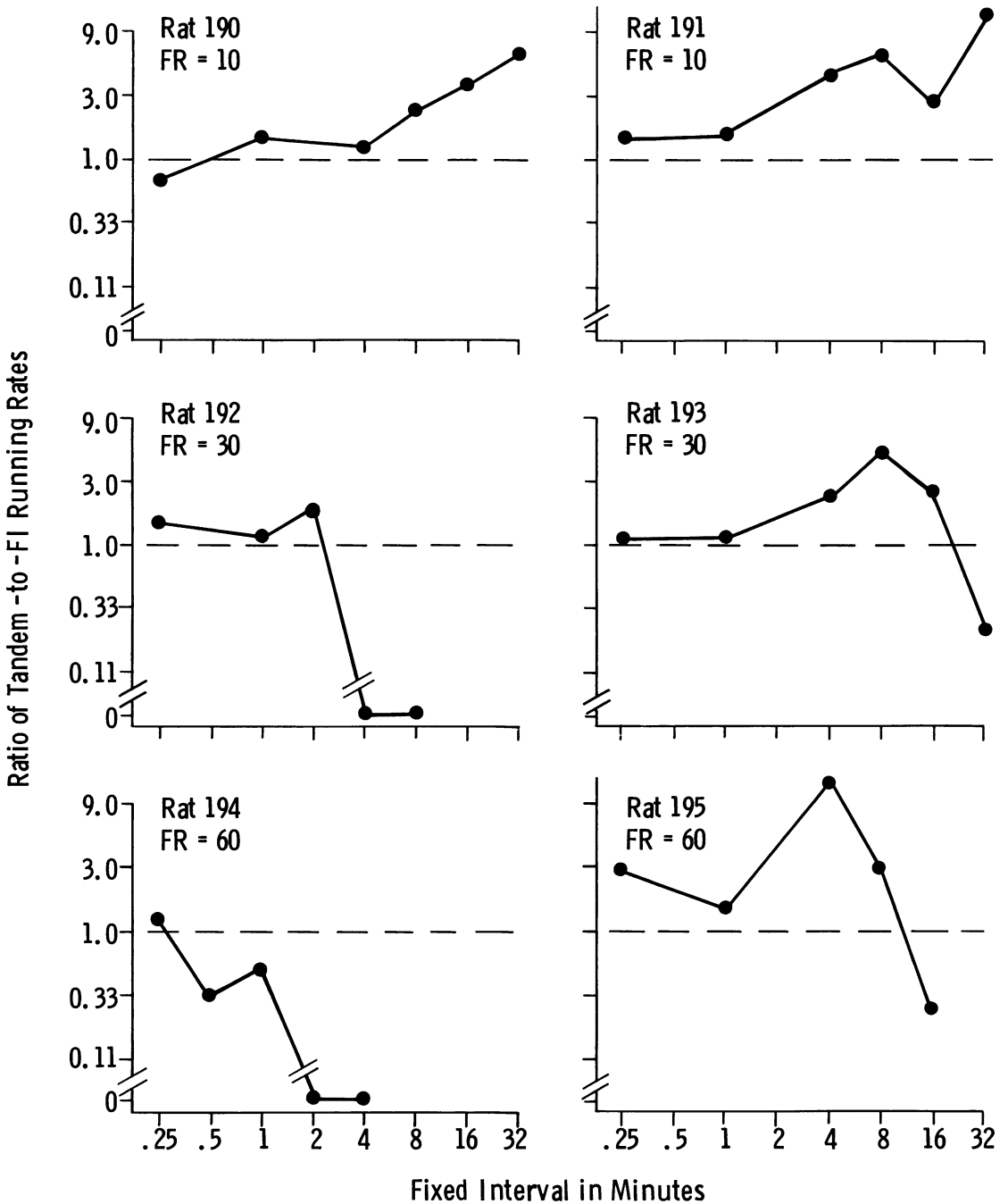


Fig. 4. Ratios of mean running response rates under tandem FI FR schedules to mean running response rates under the corresponding basic FI schedules from the last five sessions of each experimental condition.

rats, higher response rates were maintained by the FI schedules alone than by the tandem FI FR schedules.

Absolute differences in response rates under

tandem FI FR and basic FI schedules can be seen in Figure 1. However, because response rates under both scheduling arrangements tended to decrease as FI length increased, the

absolute differences in response rates also diminished with progressively longer FI values. Figure 2 displays relative differences in response rates under the two scheduling arrangements. Data points depict ratios of response rates: response rate under a given tandem FI FR schedule divided by response rate under the corresponding basic FI schedule. The horizontal dashed lines represent response rates under the basic FI schedules. Data points above the dashed lines indicate that response rate was enhanced by an added FR requirement; data points below the dashed lines indicate that response rate was reduced by an added FR requirement.

Addition of the FR 10 requirement in tandem with basic FI schedules enhanced responding at all FI values studied, except FI 4 min for Rat 190. For both rats exposed to the added FR 10 requirement, the greatest relative enhancement of response rate occurred at the longest FI value. The addition of FR 30 or FR 60 requirements in tandem with basic FI schedules enhanced responding only at relatively short FI values. For each rat exposed to these added FR requirements, the FI eventually reached a value at which the added FR requirement reduced response rate.

Figure 3 shows mean running rates from the last five sessions of each condition. Running rates were calculated by dividing the total number of responses in a session by the difference between session time and postreinforcement pause time, where pause time consisted of time from the start of a session to the first response and time from each reinforcer delivery to the first postreinforcement response. With both basic FI and tandem FI FR schedules, running rates generally decreased as the FI was lengthened. For rats with the FR 10 response requirement, higher running rates occurred under tandem FI FR schedules than under the corresponding basic FI schedules, with one exception. For rats with FR 30 or FR 60 response requirements, tandem FI FR schedules maintained higher running rates than basic FI schedules only at relatively short FI values. At longer FI values, higher running rates were maintained by the FI schedules alone than by the tandem FI FR schedules.

Figure 4 plots ratios of running rates under tandem FI FR schedules to running rates under the corresponding basic FI schedules. The horizontal dashed lines represent running rates

under the basic FI schedules. Tandem FI FR 10 schedules maintained higher running rates than did the corresponding basic FI schedules at all FI values studied except FI 15 s for Rat 190. The extent to which running rates were enhanced by the added FR 10 requirement was greater in general at longer FI values for both Rats 190 and 191. The greatest relative enhancement of running rate occurred at the longest FI value studied for each rat. By contrast, tandem FI FR 30 and tandem FI FR 60 schedules maintained higher running rates than did the corresponding basic FI schedules only at relatively short FI values. For each rat subjected to these added FR requirements, the FI eventually reached a value at which the added FR requirement reduced running rate.

Figure 5 presents reinforcement frequency, obtained reinforcers per minute, plotted against the reciprocal of the scheduled FI. Filled circles are from basic FI schedules and unfilled circles are from tandem FI FR schedules. Data points represent means from the last five sessions of each experimental condition. Diagonal lines indicate the limits on reinforcement frequency imposed by FI values along a continuous dimension. Obtained reinforcement frequency was nearly the maximum allowable under each basic FI schedule studied. For rats with the added FR 10 requirement, obtained reinforcement frequency under tandem FI FR schedules was only slightly less than that under the corresponding basic FI schedules. In contrast, the addition of FR 30 or FR 60 requirements in tandem with basic FI schedules resulted in relatively greater reductions in obtained reinforcement frequency. The greatest reductions in obtained reinforcement frequency occurred when FR 30 or FR 60 requirements were added in tandem with the longest FI value studied for each rat.

Table 2 provides mean overall response rates, reinforcement frequencies, and postreinforcement pause durations from the last five sessions of each experimental condition for each rat. Ranges of the daily means, from which the grand means in Table 2 were calculated, also are provided.

DISCUSSION

In the present study, the addition of an FR 10 requirement in tandem with basic FI schedules never reduced responding substantially at

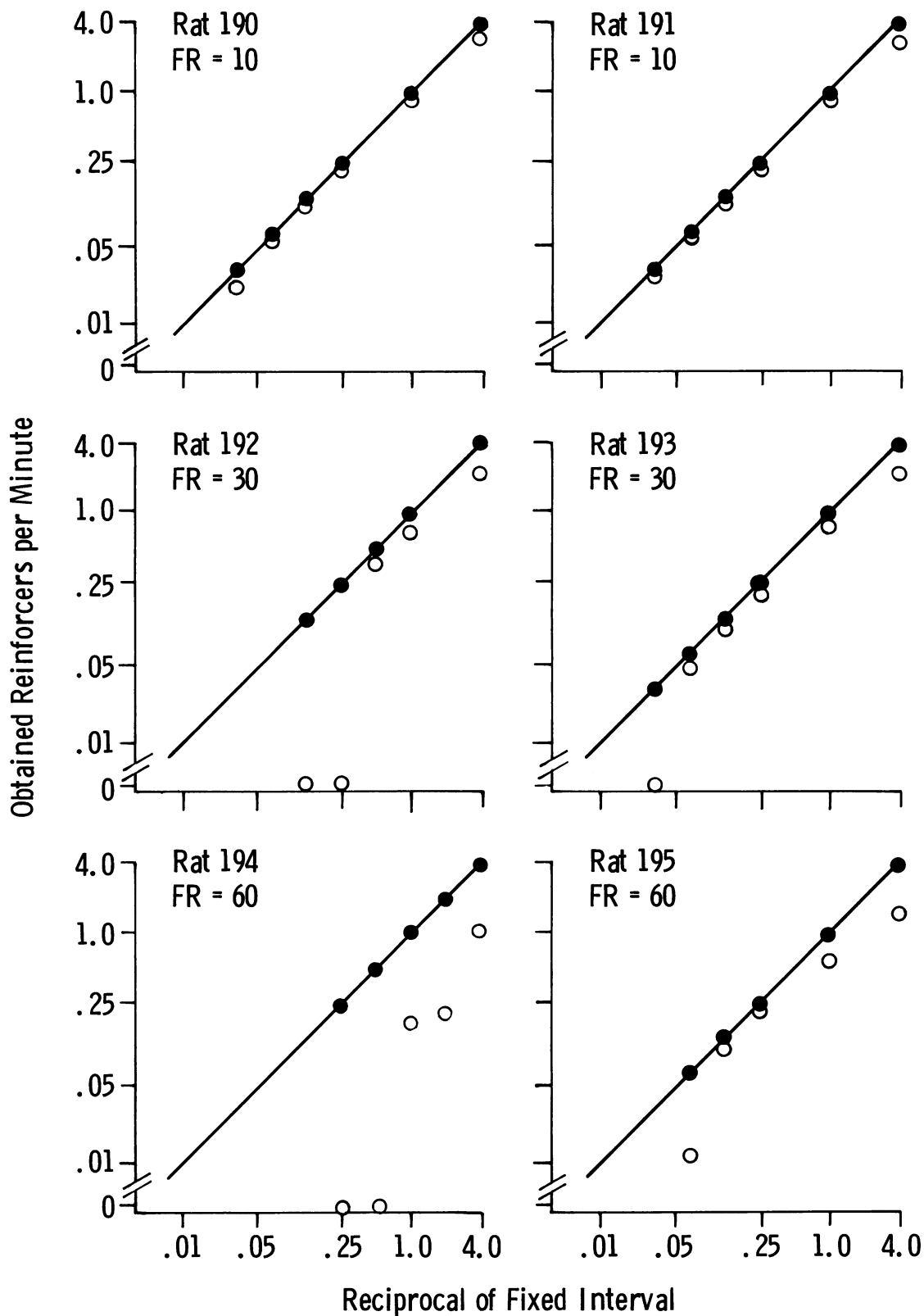


Fig. 5. Mean reinforcers per minute obtained from basic FI schedules (filled circles) and tandem FI FR schedules (open circles) over the last five sessions of each experimental condition.

Table 2

Responses and reinforcers per minute and postreinforcement pause duration in seconds over the last five sessions of each experimental condition.

Schedule	Responses per minute		Reinforcers per minute		Pause duration	
	<i>M</i>	Range	<i>M</i>	Range	<i>M</i>	Range
Rat 190						
FI 15 s	29.5	25.7-30.7	3.88	3.71-3.96	10.6	9.4-11.2
Tandem	43.3	38.4-47.7	2.72	2.58-2.82	8.4	6.0-9.7
FI 1 min	18.8	17.5-20.5	0.97	0.95-0.99	52.2	50.2-53.8
Tandem	26.9	24.3-28.6	0.92	0.92-0.93	55.0	53.7-56.5
FI 4 min	24.5	21.3-27.5	0.24	0.24-0.25	116.0	101.0-136.2
Tandem	22.1	18.9-25.4	0.23	0.22-0.24	159.2	150.8-174.9
FI 8 min	7.0	5.9-7.8	0.12	0.12-0.13	181.7	159.4-196.4
Tandem	14.9	13.7-16.0	0.12	0.11-0.12	199.2	163.4-240.3
FI 16 min	2.0	1.6-2.4	0.06	0.06-0.06	284.1	188.4-381.5
Tandem	4.4	3.0-5.9	0.06	0.05-0.06	611.1	431.9-702.6
FI 32 min	0.4	0.3-0.5	0.03	0.03-0.03	597.8	390.1-880.4
Tandem	1.4	0.3-4.0	0.02	0.02-0.03	1,814.8	1,190.3-2,742.9
Rat 191						
FI 15 s	27.0	26.0-28.3	3.88	3.86-3.90	9.7	9.4-10.2
Tandem	41.3	38.8-43.8	2.69	2.52-2.80	13.1	12.5-14.8
FI 1 min	17.5	16.9-18.2	0.99	0.98-1.00	32.2	30.2-33.3
Tandem	18.6	17.4-19.6	0.83	0.81-0.85	47.9	45.5-49.8
FI 4 min	3.9	3.3-4.5	0.24	0.23-0.24	103.1	88.8-118.1
Tandem	11.9	10.4-12.7	0.23	0.22-0.23	149.0	139.3-161.5
FI 8 min	1.6	1.3-1.8	0.12	0.12-0.12	214.0	171.8-252.4
Tandem	6.5	5.5-7.7	0.11	0.09-0.12	329.0	243.1-436.3
FI 16 min	2.3	1.0-3.9	0.06	0.06-0.06	453.2	279.8-619.0
Tandem	6.1	3.7-10.2	0.06	0.04-0.06	493.1	407.3-583.9
FI 32 min	0.3	0.1-0.5	0.03	0.03-0.03	935.4	819.1-1,055.4
Tandem	3.5	1.8-5.2	0.03	0.03-0.03	668.5	600.6-751.5
Rat 192						
FI 15 s	30.8	27.9-34.2	3.91	3.82-3.96	9.4	8.7-10.1
Tandem	82.2	78.3-84.8	2.18	2.07-2.36	8.4	7.5-9.8
FI 1 min	17.1	14.5-19.3	0.99	0.98-0.99	46.6	43.1-49.2
Tandem	29.1	27.6-30.9	0.69	0.67-0.70	55.8	54.7-56.8
FI 2 min	10.0	8.5-11.2	0.48	0.48-0.49	81.1	72.9-93.1
Tandem	20.2	18.4-22.4	0.35	0.32-0.41	111.6	90.9-134.3
FI 4 min	4.1	3.5-4.6	0.23	0.21-0.24	126.0	112.0-149.6
Tandem	0.0	0.0-0.1	0.00	0.00-0.00	—	—
FI 8 min	1.5	0.9-2.5	0.11	0.11-0.12	267.6	182.4-324.4
Tandem	0.0	0.0-0.1	0.00	0.00-0.00	—	—
Rat 193						
FI 15 s	9.3	8.1-10.5	3.75	3.70-3.81	14.9	14.5-15.3
Tandem	90.5	82.8-95.8	2.22	2.07-2.36	10.5	9.5-11.3
FI 1 min	37.2	34.8-38.9	1.00	0.99-1.00	37.5	34.1-39.0
Tandem	43.3	37.7-45.6	0.78	0.74-0.83	46.8	45.3-50.1
FI 4 min	13.4	12.1-14.7	0.25	0.24-0.25	121.1	111.1-133.8
Tandem	20.1	18.6-22.0	0.20	0.17-0.21	203.2	190.3-230.0
FI 8 min	4.9	2.5-6.4	0.12	0.12-0.12	216.9	137.8-298.3
Tandem	11.7	9.5-15.3	0.10	0.09-0.11	404.5	348.3-469.3
FI 16 min	1.6	1.1-2.2	0.06	0.06-0.06	557.2	473.9-709.4
Tandem	3.8	2.1-5.9	0.04	0.04-0.05	631.1	462.2-861.3
FI 32 min	0.5	0.2-0.8	0.03	0.03-0.03	634.3	382.1-957.0
Tandem	0.2	0.1-0.3	0.004	0.002-0.005	—	—

Table 2 (Continued)

Schedule	Responses per minute		Reinforcers per minute		Pause duration	
	<i>M</i>	Range	<i>M</i>	Range	<i>M</i>	Range
Rat 194						
FI 15 s	53.9	50.7–55.7	3.88	3.52–4.00	6.4	5.8–7.4
Tandem	67.0	60.6–75.7	1.01	0.89–1.16	23.8	18.2–28.1
FI 30 s	7.0	5.7–7.7	1.90	1.83–1.93	28.5	27.1–30.6
Tandem	13.2	11.4–16.6	0.21	0.18–0.27	127.2	87.1–159.0
FI 1 min	14.4	13.3–16.5	0.97	0.96–0.98	40.7	38.3–43.2
Tandem	10.3	9.0–11.2	0.16	0.14–0.18	192.8	138.1–244.8
FI 2 min	11.7	10.0–13.5	0.48	0.47–0.49	79.8	66.1–87.9
Tandem	0.2	0.0–0.4	0.00	0.00–0.00	—	—
FI 4 min	4.2	3.6–4.7	0.23	0.22–0.24	133.1	110.8–166.1
Tandem	0.1	0.0–0.1	0.00	0.00–0.00	—	—
Rat 195						
FI 15 s	35.6	31.0–39.7	3.73	3.72–3.75	4.1	3.9–4.2
Tandem	115.1	105.9–123.9	1.48	1.35–1.62	7.0	5.9–9.3
FI 1 min	38.6	35.4–40.6	0.97	0.97–0.99	24.7	21.5–26.5
Tandem	50.0	43.0–53.6	0.59	0.56–0.64	47.3	39.1–59.6
FI 4 min	4.1	3.6–4.7	0.24	0.24–0.24	111.9	104.4–126.6
Tandem	39.0	38.4–39.6	0.22	0.21–0.23	154.5	136.6–172.1
FI 8 min	6.1	5.4–6.8	0.12	0.12–0.12	181.2	130.2–226.3
Tandem	15.4	12.8–18.6	0.10	0.07–0.11	298.1	201.4–489.2
FI 16 min	3.1	2.1–4.4	0.06	0.06–0.06	292.8	225.5–342.6
Tandem	0.8	0.5–1.1	0.01	0.00–0.02	—	—

any FI value studied, from 15 s to 32 min. The enhancement of both overall response rate and running rate, relative to that maintained by basic FI schedules, was greatest at the longest FI values studied. By contrast, the addition of an FR 30 or an FR 60 requirement in tandem with basic FI schedules enhanced responding only at relatively short FI values. At longer FI values, these added response requirements reduced responding relative to that maintained by the basic FI schedule alone. The FI value at which the effect of the added response requirements changed from response enhancement to response reduction was different for each rat. Nonetheless, the trend for each rat was clear: As the FI value was increased over experimental conditions, FI length eventually reached a value at which the added FR requirement substantially reduced both overall response rate and running rate.

The present study also provides parametric data on FI performance by rats. Postreinforcement pause duration was an increasing monotonic function of FI length and, with few exceptions, overall response rate was a decreasing

monotonic function of FI length. These findings are consistent with previous research on FI schedules, both with rats (e.g., Dukich & Lee, 1973; Harzem, Lowe, & Spencer, 1978; Lowe & Harzem, 1977; Lowe, Harzem, & Spencer, 1979; Rider, 1980; Sherman, 1959, cited in Nevin, 1973; Skinner, 1938; Wilson, 1954) and with pigeons (e.g., Lowe & Harzem, 1977; Lowe et al., 1979; Schneider, 1969; Zeiler & Davis, 1978). The proportion of the FI occupied by the postreinforcement pause in the present study tended to decrease as FI length increased. This result is in accord with findings by Lowe et al. (1979), with both rats and pigeons, but it is inconsistent with the notion that the pause is a linear function of the interreinforcement interval (e.g., Dukich & Lee, 1973; Nevin, 1973; Rider & Kametani, 1984, 1987). Pause data from relatively long FIs (and from the corresponding tandem schedules) in the present study should be viewed with some caution, however, because the mean pause durations listed in Table 2 were calculated from sessions containing as few as four individual pauses.

Zeiler and Buchman (1979) proposed that response strength is a joint function of the frequency of reinforcement and the response requirement. Rate of responding is enhanced both by increases in reinforcement frequency and by increases in the response requirement. The response-enhancing effect of response requirements can be seen in the different rates of responding generated by time and interval schedules. Time schedules, which provide reinforcers independently of responding, impose no response requirement (Zeiler, 1968). Interval schedules, which differ only by requiring a single response after the scheduled interval has elapsed, nonetheless maintain considerably higher response rates than time schedules do (e.g., Herrnstein, 1966; Lowe & Harzem, 1977; Zeiler, 1968, 1977). By adding FR requirements in tandem with basic FI schedules, the response requirement is increased and responding is enhanced further. But because reinforcement frequency necessarily decreases when a multiple-response requirement is imposed in tandem with a basic interval schedule, the net effect on response rate depends on the size of the added response requirement. This is a reinforcement-theory account of responding in that reinforcement frequency and the response requirement "... are viewed as parameters of the reinforcement operation that controls the strength of operant responding" (Zeiler & Buchman, 1979, p. 44).

In between-subjects comparisons, Zeiler and Buchman (1979) found no systematic effect of FI length on responding under either tandem or conjunctive FI FR schedules. Consistent effects were obtained in the present study by manipulating FI length within subjects. Although Zeiler and Buchman concluded that FI length did not mitigate the effect of added response requirements, the present findings support their account of responding as a joint function of reinforcement frequency and the response requirement.

If an FR requirement added to a basic FI schedule is small enough to produce only a trivial effect on reinforcement frequency, then the effect on responding of that reduction in reinforcement frequency is apt to be trivial regardless of the length of the basic FI. Because response strength increases with the response requirement, the net effect of such relatively small added response requirements is an enhancement of responding. In the present experiment, responding was enhanced by the

added FR 10 requirement in tandem with FI schedules as long as 32 min; the extent of that enhancement showed no trend toward diminishing with increasing length of the FI.

By contrast, if an FR requirement is large enough to have a substantial effect on reinforcement frequency, then the effect on responding of that reduction in reinforcement frequency is apt to be substantial. If so, the net effect on responding would depend at least to some extent on the length of the FI, as that limits the overall frequency of reinforcement that remains after the reduction. With the addition of either an FR 30 or an FR 60 requirement to short FIs in the present study, reinforcement frequency remained sufficiently high, despite the decrement accompanying the added response requirements, that responding was enhanced relative to that maintained by the FI alone. With the addition of the same response requirements to longer FIs, reinforcement frequency became sufficiently low that responding weakened or ceased altogether.

REFERENCES

- Baum, W. M. (1981). Optimization and the matching law as accounts of instrumental behavior. *Journal of the Experimental Analysis of Behavior*, **36**, 387-403.
- Catania, A. C., Matthews, T. J., Silverman, P. J., & Yohalem, R. (1977). Yoked variable-ratio and variable-interval responding in pigeons. *Journal of the Experimental Analysis of Behavior*, **28**, 155-161.
- Dukich, T. D., & Lee, A. E. (1973). A comparison of measures of responding under fixed-interval schedules. *Journal of the Experimental Analysis of Behavior*, **20**, 281-290.
- Ferster, C. B., & Skinner, B. F. (1957). *Schedules of reinforcement*. New York: Appleton-Century-Crofts.
- Harzem, P., Lowe, C. F., & Spencer, P. T. (1978). Temporal control of behavior: Schedule interactions. *Journal of the Experimental Analysis of Behavior*, **30**, 255-270.
- Herrnstein, R. J. (1966). Superstition: A corollary of the principles of operant conditioning. In W. K. Honig (Ed.), *Operant behavior: Areas of research and application* (pp. 33-51). New York: Appleton-Century-Crofts.
- Herrnstein, R. J. (1970). On the law of effect. *Journal of the Experimental Analysis of Behavior*, **13**, 243-266.
- Herrnstein, R. J., & Morse, W. H. (1958). A conjunctive schedule of reinforcement. *Journal of the Experimental Analysis of Behavior*, **1**, 15-24.
- Killeen, P. (1969). Reinforcement frequency and contingency as factors in fixed-ratio behavior. *Journal of the Experimental Analysis of Behavior*, **12**, 391-395.
- Kintsch, W. (1965). Frequency distribution of interresponse times during VI and VR reinforcement. *Journal of the Experimental Analysis of Behavior*, **8**, 347-352.
- Lowe, C. F., & Harzem, P. (1977). Species differences

- in temporal control of behavior. *Journal of the Experimental Analysis of Behavior*, **28**, 189-201.
- Lowe, C. F., Harzem, P., & Spencer, P. T. (1979). Temporal control of behavior and the power law. *Journal of the Experimental Analysis of Behavior*, **31**, 333-343.
- Matthews, B. A., Shimoff, E., Catania, A. C., & Sagvolden, T. (1977). Uninstructed human responding: Sensitivity to ratio and interval contingencies. *Journal of the Experimental Analysis of Behavior*, **27**, 453-467.
- Nevin, J. A. (1973). The maintenance of behavior. In J. A. Nevin & G. S. Reynolds (Eds.), *The study of behavior: Learning, motivation, emotion, and instinct* (pp. 201-236). Glenview, IL: Scott, Foresman.
- Rider, D. P. (1977). Interlocking schedules: The relationship between response and time requirements. *Journal of the Experimental Analysis of Behavior*, **28**, 41-46.
- Rider, D. P. (1980). Alternative fixed-ratio fixed-interval schedules of reinforcement. *Journal of the Experimental Analysis of Behavior*, **33**, 243-252.
- Rider, D. P. (1982). Sensitivity of responding to simple vs. complex contingencies of reinforcement. *Psychological Record*, **32**, 365-374.
- Rider, D. P., & Kametani, N. N. (1984). Interreinforcement time, work time, and the postreinforcement pause. *Journal of the Experimental Analysis of Behavior*, **42**, 305-319.
- Rider, D. P., & Kametani, N. N. (1987). Intermittent reinforcement of a continuous response. *Journal of the Experimental Analysis of Behavior*, **47**, 81-95.
- Schneider, B. A. (1969). A two-state analysis of fixed-interval responding in the pigeon. *Journal of the Experimental Analysis of Behavior*, **12**, 677-687.
- Sherman, J. G. (1959). *The temporal distribution of responses on fixed-interval schedules*. Unpublished doctoral dissertation, Columbia University.
- Shimoff, E., Matthews, B. A., & Catania, A. C. (1986). Human operant performance: Sensitivity and pseudosensitivity to contingencies. *Journal of the Experimental Analysis of Behavior*, **46**, 149-157.
- Skinner, B. F. (1938). *The behavior of organisms*. New York: Appleton-Century.
- Williams, D. R. (1968). The structure of response rate. *Journal of the Experimental Analysis of Behavior*, **11**, 251-258.
- Wilson, M. P. (1954). Periodic reinforcement interval and number of periodic reinforcements as parameters of response strength. *Journal of Comparative and Physiological Psychology*, **47**, 51-56.
- Zeiler, M. D. (1968). Fixed and variable schedules of response-independent reinforcement. *Journal of the Experimental Analysis of Behavior*, **11**, 405-414.
- Zeiler, M. (1977). Schedules of reinforcement: The controlling variables. In W. K. Honig & J. E. R. Staddon (Eds.), *Handbook of operant behavior* (pp. 201-232). Englewood Cliffs, NJ: Prentice-Hall.
- Zeiler, M. D. (1979). Output dynamics. In M. D. Zeiler & P. Harzem (Eds.), *Advances in analysis of behaviour: Vol. 1. Reinforcement and the organization of behaviour* (pp. 79-115). Chichester, England: Wiley.
- Zeiler, M. D., & Buchman, I. B. (1979). Response requirements as constraints on output. *Journal of the Experimental Analysis of Behavior*, **32**, 29-49.
- Zeiler, M. D., & Davis, E. R. (1978). Clustering in the output of behavior. *Journal of the Experimental Analysis of Behavior*, **29**, 363-374.
- Zuriff, G. E. (1970). A comparison of variable-ratio and variable-interval schedules of reinforcement. *Journal of the Experimental Analysis of Behavior*, **13**, 369-374.

Received September 16, 1988
Final acceptance June 11, 1989